A Prototype Real-Time Wide Area Differential GPS System

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SATLOC

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Biography

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Yoaz Bar-Sever has a Ph.D. in Applied Mathematics from the Technion - Israel Institute of Technology and a M.S. in Electrical Engineering from the University of Southern California. Since 1989 he has been a member of the Earth Orbiter System Group at JPL where his current focus is on high precision orbit determination with GPS and its applications in Earth sciences.

Bruce Haines received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon Science Working Team, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

Byron Iijima is a member of the GPS Networks and Operations Group at the Jet Propulsion Laboratory in Pasadena CA. For the last 8 years he has been developing technology for deep-space and GPS tracking applications. He is currently focused on GPS-based ionospheric maps, especially in real-time applications. He holds a Ph.D. in physics from MIT.

Stephen Lichten has worked at the Jet Propulsion Laboratory since 1983, where he presently is the Earth Orbiter Systems Group Supervisor and Radio Metrics manager in NASA's Deep Space Network Technology Program. He received a Ph.D. in astrophysics from Caltech in 1983. His group specializes in technology development for high-precision navigation, geodetic and atmospheric applications, emphasizing automated GPS tracking techniques and software. Recently, Dr. Lichten's group has developed high-precision real-time software which has been licensed for operational use in the FAA's GPS Wide Area Augmentation System (WAAS).

Ulf Lindqwister received his Ph.D. in physics from Princeton University, Princeton, in 1988. He has been working in the Tracking Systems and Applications section since he began at JPL in 1988 and is currently supervisor of the GPS Networks and Ionospheric Systems Development group. In recent years his work has been focused on the development of NASA's permanent GPS ground tracking network and on developing research and development applications of the global ionospheric mapping technique.

Angelyn Moore received her Ph.D. in Physics from the University of California, Riverside, in 1995. She began working at JPL in 1987, performing her undergraduate and graduate research in the area of ultrastable trapped-ion frequency standards. Since 1995 she has been a member of the GPS Networks and Ionospheric Systems Development Group, primarily developing near real-time systems for global ionospheric determination using a global network of GPS ground stations.

Ronald Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a Member of the Technical Staff in the Earth Orbiter Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on the development of efficient filtering/smoothing software for

An expansion of WADGPS to global use would have far-reaching impact. A reliable real-time precision global positioning capability can, for instance, provide autonomous spacecraft navigation, reducing operations costs for NASA and commercial space missions.

There are some applications for which higher accuracies, from the 1-meter to sub-decimeter level, are desired. These include real time docking and proximity operations in space. Other high precision applications will come from NASA-supported science activities and from commercial efforts around the world, examples of which include: satellite remote sensing, in situ Earth science on land and water, synthetic aperture radar (SAR) imaging, topographic mapping, ocean and land altimetry, precision surveying applications, and gravimetry. Measurement platforms requiring precise real-time positioning may include satellites, balloons, aircraft, ships and bouys. For interferometric mapping applications, the high-accuracy global WADGPS capability would enable significant operational cost savings and major enhancements in areas such as natural hazard monitoring. While for many, these accuracies are not necessarily needed in real time, the ability to achieve such accuracy autonomously onboard would save considerable time and expense on the ground. A real-time onboard capability for autonomous navigation and production of precision science products is a key element in NASA's New Millennium Program.

The system described in this paper could be broadened into a global system capable of supporting high precision real-time user positioning anywhere in the world or in the low-Earth space regime. With the current software, ground user accuracies at the several decimeter level have been demonstrated. A long-term objective is to develop a capability for seamless global real-time accuracy at the sub-10 cm level, through algorithm enhancements and modified operations, effectively equalling local area DGPS performance worldwide

The agriculture industry, in particular, has developed a need for highly accurate positioning to support the emerging field of precision farming. Precision farming concepts are being applied to two main areas: yield mapping and soil sampling. Soil fertility mapping has been a natural extension of attempts to understand and manage crop yield variations. The potential to target herbicide application to specific weeds and weed patches offers an opportunity to improve management, reduce herbicide application and save money. Because applying chemical fertilizers is expensive, farmers can reduce costs through accurate application in areas where soil sampling shows a specific need.

The results in this paper were achieved using GPS tracking data from a ground network recently implemented by SATLOC, a company active in the use of precision DGPS for agriculture.

System Overview

Figure 1, shows the SATLOC network of 14 fixed Ashtech Z12 ground receivers (circles) which return data to a SATLOC central processing facility in Arizona at a 1-Hz rate. These data are then reformatted and sent to the Jet Propulsion Laboratory (JPL) in California for processing, arriving with a latency from time of reception at the receiver of about 1.6 seconds. After the initial engineering checkout, the processing facility will be moved from JPL to SATLOC's facility. Figure 2 shows a block diagram of the processing performed at JPL. GPS orbits and troposphere delays at the receiver are determined at a 15-min update interval using precise dynamic models with dual frequency data smoothed to 3 minutes. Ionosphere calibrations for single frequency users are updated every 15 minutes using data smoothed to 5 minutes. Slowly varying inter-frequency biases at all the receivers and the GPS satellite transmitters are determined once and monitored every 2 weeks. Range corrections to the GPS constellation, dominated by SA clock dither, are determined every second and projected a few seconds into the future to account for system latency (dominated by network communications).

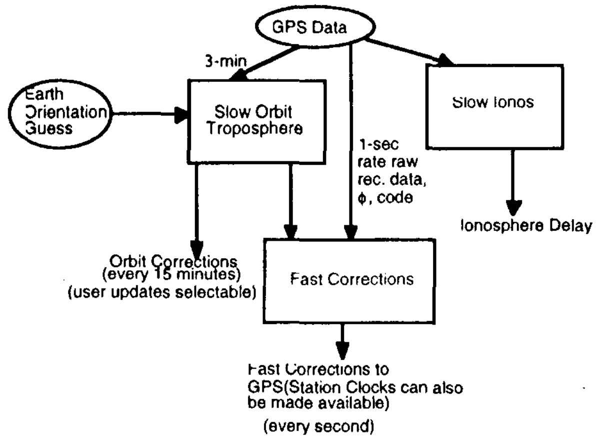

Fig. 2, Data Processing Block Diagram

measured against precise post-processed truth orbits is 1.3 m using the 14 SATLOC ground receivers in the large rectangle including North America from 20° to 60° North latitude and 210° to 310° longitude, Fig. 1, with a 2-D (horizontal) RMS accuracy of 1.2 m. Note that it is the 2-D RMS that is the most significant figure of merit in a wide area differential GPS system. If the network is augmented with 6 receivers in Alaska, Hawaii, Western Canada, and the Caribbean (squares in Fig. 1), the 3-D RMS accuracy falls to 80 cm with a corresponding 2-D RMS of 75 cm. With a global ground network, initial tests indicate that real-time accuracies better than 40 cm for GPS orbits can be achieved.

The zenith delay troposphere at each of the 14 ground stations is treated as a random-walk process in time with a stochastic update every 3 minutes. It is mapped to GPS line of sight using the Niell mapping function [*Niell*, 1996]. The noise added at each stochastic update is 0.17 cm/sec$^{1/2}$. The value at the end of the 15 minute data batch is then used by the fast correction process as a constant value in the next 15 minutes. For a typical 24 hour period shown in Table 1(-see Fig. 3 for locations), the 15 minute predictor has an RMS difference with truth of about 1.7 cm. The truth troposphere is determined by post-processing the GPS data. The accuracy of post-processed GPS troposphere delays has been validated against water vapor radiometers and Very Long Baseline Interferometry (VLBI) techniques at the sub-centimeter level [*Bar-Sever and Kroger*, 1996; *Trali and Lichten*, 1990; *Tralli et al.*, 1976].

The accuracy of the orbit and troposphere solutions and the exploitation of precise and well-tested dynamic and measurement modeling for GPS observables enables the WADGPS system described here to strongly separate the effects of GPS orbits and clocks (including SA). Such separation of physically different effects is a key feature of this software which provides significant advantages when testing for outliers and performing integrity checks.

Ionosphere Calibrations

The process for generation of precise real-time ionospheric delay corrections utilizes a modified version of the Global Ionosphere Map (GIM) software developed at JPL [*Mannucci, et al.* 1993]. GIM has been extensively used and validated in non-real-time applications since 1993 [*Mannucci, et al.* 1995]. GIM takes dual-frequency GPS tracking data from a network of GPS receivers and produces maps of the electron content of the ionosphere. GIM's FORTRAN-based programs have been automated for real-time operations with a set of Unix scripts, and have been successfully processing real-time GPS data from the SATLOC WADGPS network since September 1996. Parts of the GIM software are currently being converted to ANSI c and integrated with the RTG software package, as described below, so that the process can run more efficiently. This real-time ionosphere software will also eventually be integrated into the FAA's operational WAAS software.

Table 1, Troposphere Accuracy Compared to Post-processed Truth

Station	RMS Within Data Arc	RMS 15 Minute Prediction
BEMI	1.06 cm	1.07 cm
FRIE	2.35 cm	2.46 cm
FTPI	1.82 cm	1.92 cm
HAYD	1.20 cm	1.24 cm
LAJO	1.68 cm	1.74 cm
LINC	1.17 cm	1.22 cm
OLYM	1.84 cm	1.91 cm
ORON	1.71 cm	1.71 cm
RICH	1.48 cm	1.51 cm
ROSW	1.63 cm	1.68 cm
STIG	1.07 cm	1.20 cm
Average RMS	**1.59 cm**	**1.65 cm**

Every 15 minutes the ionospheric correction process wakes up and processes the previous 15 minutes of dual-frequency GPS tracking data smoothed to 5 minute data points. A Kalman filter is used to produce sequentially updated maps. The ionosphere is modeled as a thin spherical shell at an altitude of 450 km. The ionosphere's electron content on this shell is parameterized by the values of electron content at the vertices of a highly uniform triangular grid on the shell. The spatial variation of the electron density between the vertices is modeled as linear. We fix the grid in the solar-magnetic frame (sun-fixed or local-time frame) since the ionospheric density is relatively stationary in that frame. (The ionosphere changes rapidly in an earth-fixed frame, with the greatest electron density appearing at ~2 pm local time.) The density at each vertex is modeled stochastically with carefully tuned time correlations between updates.

To assess ionospheric calibration accuracy, data were collected from two North American networks, shown in Fig. 4. on 2 Sept 96. The solid circles indicate the transmitters and ground GPS receivers. The GIM software is also used to extract each of these L1/L2 delays (relative to one receiver whose hardware should be calibrated for absolute determination) from the GPS tracking data as described in *Mannucci, et al.* 1995. In addition to the ionosphere calibration, the interfrequency biases are necessary for calibration of the GPS clocks (T_{GD}) by a single-frequency user[*Van Dierendonck, et al.*, 1980].

Table 2 contains a complete set of absolute satellite biases (T_{GD}) obtained from GIM estimates, along with the current broadcast values. The satellite biases are expressed in nanoseconds at L1. The GIM estimates are 10-day averages of daily GIM runs using 98 GPS sites (of which ~60 contribute to improved global coverage). Repeatability of the biases is currently at the level of 0.2 ns at L1. Accuracy studies over several years (*Wilson et al.*, 1994) and comparions of GIM results to independent ionospheric measurements from the TOPEX dual-frequency altimeter (*Mannucci et al.*, 1995) indicate that the satellite biases are accurate to 0.5 ns at L1. The current broadcast values are based on pre-launch measurements and differ quite markedly from the well-accepted values published by us and by other groups (*Sardon et al.*, 1993).

Real-Time GIPSY (RTG)

GOA II is not a software suited to real-time processing at high data rates (1-Hz). In order to accommodate the high data rates of the 1-Hz range corrections, an enhanced software system called Real-Time Gipsy (RTG) was written in ANSI C. RTG'S original design goals included 1) incorporation of all the precise models of GOA II; 2) suitability for use in imbedded systems such as a GPS receiver (earth based or orbiting); and 3) real-time processing. For WADGPS applications, RTG is hosted on a UNIX workstation (HP, IBM, or Sun). It is also being adapted for implementation in WAAS for real-time computation of both the fast range corrections and the slow orbit and troposphere corrections. In addition, modules are also shared with the WAAS ionosphere prototype. RTG is also being used at JPL to perform real-time user positioning to validate WADGPS corrections. As discussed above, our current prototype is temporarily utilizing GOA II for the orbit and troposphere slow-rate WADGPS corrections and RTG for the fast range corrections. However, RTG is being updated for the slow orbit and troposphere corrections.

1-Hz Fast Range Corrections

For every satellite viewed by the network, a correction to the GPS range is computed every second. This correction is solved for as a correction to the GPS clock, which is estimated simultaneously with the receiver clocks . This allows for isolation and identification of error sources as GPS or receiver problems. Note that even over North America some orbit error is common to all the receivers viewing GPS and is absorbed by the GPS clock solution. For this reason we refer to it as a GPS range correction.

Fig. 6 is a block diagram of the process. Almost all of the computation can be carried out during the network communication process and thus the fast correction computation adds only about 2 msec to the latency of the corrections.

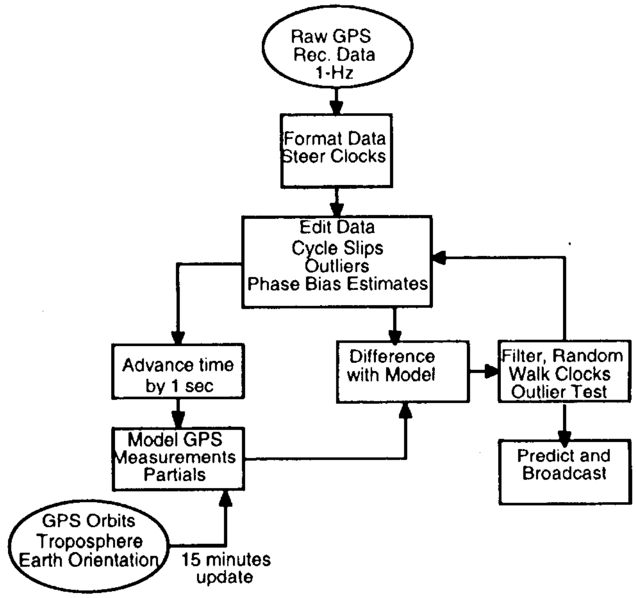

Fig. 6 Fast Correction Processing Block Diagram

Data Formatting, Clock Steering

After the data are formatted by the SATLOC data facility for re-transmission to JPL, they are re-formatted to an internal RTG data structure. At this point the data are adjusted for the GPS broadcast clock values. Most of the receivers in the network are run off the receiver's internal crystal oscillator. The receivers reset their clock values when the clock drifts more than 1 msec from GPS time as detected by the receiver's navigation solution. A discontinuous change in the data is performed by the receiver. Instead of allowing this discontinuity, we residual is rejected and not processed by the filter. In the fast correction process, if a measurement is rejected by the filter a cycle break will be inserted at that time in the data editor. An innovations scaling factor of 5 was used in the fast correction process. Table 3 shows a typical set of statistics accumulated after 5 hours of processing on Dec. 16, 1996.

Table 3, Outlier detection by Receiver and GPS.

Receiver/ GPS	Number of Outliers Detected by Innovations Test	Number of Data Points	Percentage of Bad Points
LAJO:	6051	85382	7.1
RICH:	3003	100183	3.0
ORON:	2498	96998	2.6
HAVR:	2597	99338	2.6
ARCA:	2650	101208	2.6
STIG:	2114	107089	2.0
BEMI:	1864	104072	1.8
LINC:	1440	98633	1.5
ROSW:	1364	111647	1.2
FTPI:	550	112108	0.5
QUIS:	388	109730	0.4
GPS31	2604	22097	11.8
GPS16	8403	121791	6.9
GPS27	455	6696	6.8
GPS22	6625	175692	3.8
GPS33	2095	66396	3.2
GPS40	37	1435	2.6
GPS18	1446	111922	1.3
GPS19	713	66956	1.1
GPS29	2100	225854	0.9

Fig. 7 shows a typical set of corrections for all the PRN's in view by the network for 5 minutes. The values are typical of SA except for PRN15 which has SA off. During this period PRN15 was only observed by a few stations at the edge of the SATLOC network, resulting in slightly noisier corrections. The best observed GPS have formal errors on the corrections of around 10 cm whereas PRN15 had a formal error of about 50 cm.

Correction Broadcast and Prediction

Due to the difference in time between the reception of the GPS data at the ground receivers and the arrival of the corrections based on those data at the user equipment, the corrections are predicted several seconds into the future.

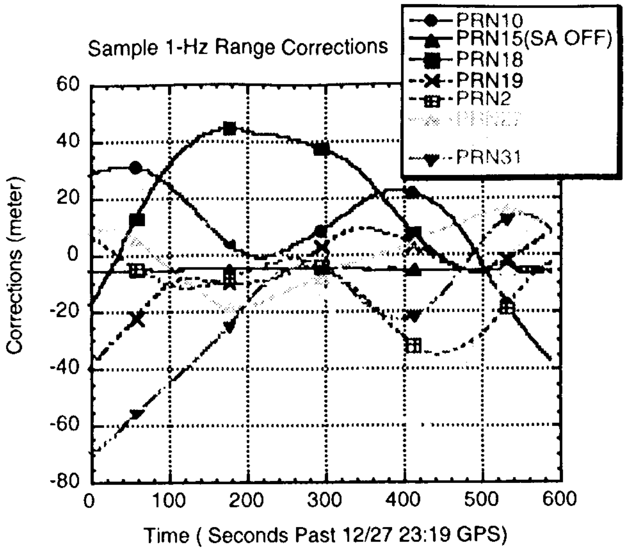

Fig. 7, Ten minute sample of range corrections produced every second.

Table 4 compares the results of two extrapolation strategies using phase data with pseudorange-fixed biases. In each case, the extrapolated value of the GPS SA clock is compared to the truth case obtained with the filter/smoothed clock solution. The data were taken on May 21, 1993 at a 1-sec rate by a TurboRogue receiver using an ovenized crystal oscillator.

Quadratic extrapolation from six 1-sec solutions reduces the error by a factor of two compared to a linear fit. Therefore, the fast correction prediction with a quadratic extrapolation from six 1-sec solutions up to current time was adopted. Constant phase biases (determined by pseudoranges) are used over all six time points to maintain continuity and thus extrapolation accuracy.

Table 4. Extrapolated SA Clock Errors

Extrapolation	No. of Points	Mean (cm)	Std. Dev. (cm)
Linear	21396	0.01	8.7
Quadratic	21396	0.01	4.3

The degradation of accuracy for fast correction prediction can be estimated by comparing the results of user point positioning using direct and predicted fast corrections, as shown in Fig. 8. The 3-D RSS differerence of 0.4±13 cm is well within the expected point positioning accuracy, set, as noted above Pseudorange outliers could be a problem for a user, but should be detectable with an improved editor in the user equipment. . Note that in the fast correction process these outliers are straightforwardly detected and eliminated with an innovations test which is not possible with user point positioning treated as a white noise process. Fig. 10 (compare with Fig. 9) shows the poor positioning results when the innovations test for outliers in the fast correction process is too loose.

Single-Frequency User Position

The single-frequency algorithm is essentially the same as the dual-frequency algorithm except that only single-frequency range and phase are used. The main change is in the data editor and its adjustment of the phase biases based on the range data. Before this adjustment is made, the data must be corrected for the ionosphere delay and the interfrequency bias in the GPS transmitters, eliminating the code carrier divergence. Since the ionosphere is smooth over several minutes, we may expect some improvement due to the lower data noise at the L1 frequency. Our current data editor merely does the ionosphere free combination for dual-frequency data at the 1-Hz rate resulting in noisier dual-frequency range used to perform the carrier phase bias determination. Some smoothing in time will be implemented in the future for dual-frequency data.

Fig. 11, shows the plot of single-frequency user positioning for comparison to Fig. 9. One can see the effects of decreased data noise on some of the plots. A close look at the single-frequency plots reveals a few small discontinuities which are not in the dual-frequency results. At least some of these are probably due to the discontinuous changes in the ionosphere nodal values in the sun-fixed frame occurring at the 15-minute updates. Overall one sees similar accuracy in the single and dual-frequency results, with few decimeter accuracy achieved most of the time.

Summary, Conclusions

A prototype WADGPS capability has been developed and demonstrated. The system has shown user positioning accuracies for both single-frequency and dual-frequency receivers at the level of a few tens of centimeters in the continental United States, where real-time data have been available. The data processing software is being developed at the Jet Propulsion Laboratory and will soon be available in a compact software package written exclusively in ANSI c. This WADGPS software package is designed to be portable on a wide variety of workstation or PC platforms. The algorithms and system design make it ideal for applications with global networks as well as with smaller regional or continental networks.

The system will find initial commercial use in a WADGPS system developed by SATLOC for precision farming applications. The JPL WADGPS software is also being adapted for operational computation of real-time corrections to support aircraft navigation with the FAA WAAS. The implementation emphasizes the use of information in the GPS carrier phase for many aspects of the WADGPS correction computation. The high fidelity of the measurement, geodetic and dynamic models employed in the software enable the fast and slow corrections to be well separated, thus facilitating integrity monitoring. The software design will make the expansion from CONUS use to global application straightforward. Future enhancements currently being explored would improve global real-time user positioning accuracy to the sub-decimeter level.

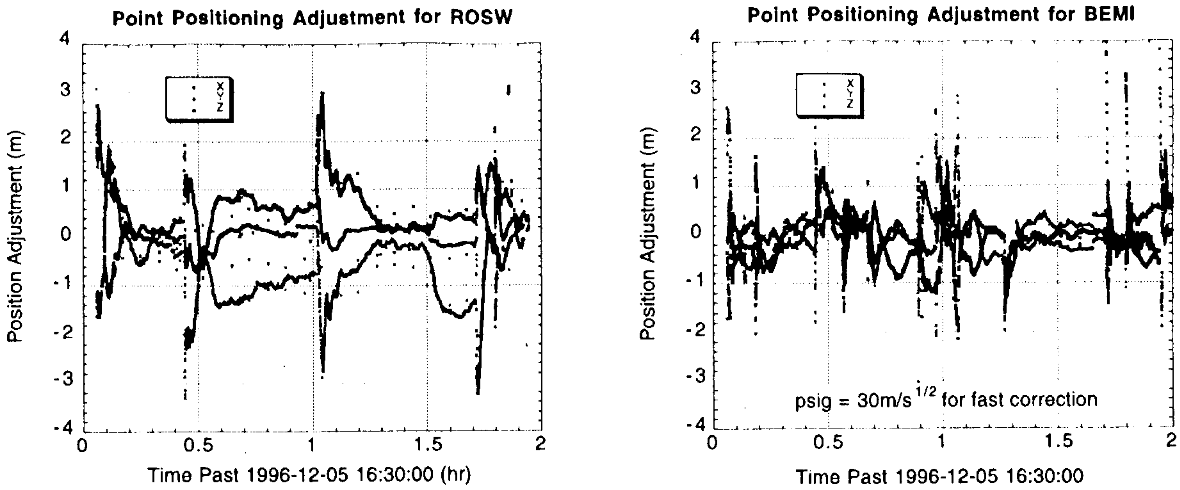

Fig. 10 Positioning due to undetected outliers in the fast corrections. Innovations test is too loose.

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